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13. ABSTRACT (Maximum 200 words)

Ultrasmall optical pumped far infrared laser cavities were constructed using defect cavities in a purely dielectric photonic crystal. Microwave measurements were performed on scale model photonic crystals to understand the performance of the cavities as a function of cavity size, isolation, and dielectric loss. In addition, continuous wave and ultrafast optical measurements of wide bandgap semiconductos were performed. Refractive indices were measured for AlGaN comprehensively for the first time. Measurements of conduction band offsets of AlGaN were attempted. The electron capture time in InGaN multiple quantum well laser structure was found to be approximately 0.5 ps when electrons are optically injected near the barrier band edge. Coherent oscilations of zone folded longitudinal acoustic phonons were observed, and the means for their generation were studied. Finally, these phonons were coherently controlled, and complete cancellation of optically generated acoustic phonons was demonstrated for the first time.

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A Millimeter-wave Photonic Crystal Laser

FINAL PROGRESS REPORT

Henry O. Everitt

May 20, 2002

U.S. ARMY RESEARCH OFFICE

DAAH04-93-D-0002

DUKE UNIVERSITY

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1. List of Manuscripts

Ü. Özgür, C.-W. Lee, and, H. O. Everitt, "Control of Coherent Acoustic Phonons", Optics in 2001, *Optics & Photonics News,* **12** (12), December 2001, p. 66.

Ü. Özgür, G. Webb-Wood, and H. O. Everitt, "Systematic Measurement of $Al_xGa_{1-x}N$ Refractive Indices," *App. Phys. Lett.*, **79** (25), 17 December 2001, pp. 4103-4105.

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J. R. Demers, T. M. Goyette, K. B. Ferrio, H. O. Everitt, B. D. Guenther, and F. C. De Lucia, "Spectral Purity and Sources of Noise in Femtosecond-Demodulation Teraherz Sources Driven by Ti: Sapphire Mode-Locked Lasers," *IEEE Journal of Quantum Electronics,* **QE-37** (4), April 2001, pp. 595-605.

Ü. Özgür, M. J. Bergmann, H. C. Casey, Jr., H. O. Everitt, A. C. Abare, S. Keller, and S. P. DenBaars, "Ultrafast Optical Characterization of Carrier Capture Times in InxGa1-xN Multiple Quantum Wells," *App. Phys. Lett.*, **77** (1), 3 July 2000, pp. 109-111.

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M.M. Beaky, J. B. Burk, H. O. Everitt, M. A. Haider, and S. Venakides, "Two Dimensional Photonic Crystal Fabry-Perot Resonators with Lossy Dielectrics," *IEEE Transactions on Microwave Theory and Techniques*, **MTT-47** (11), November 1999, pp. 2085-2091.

M.J. Bergmann, Ü. Özgür, H.C. Casey, H. O. Everitt, and J. F. Muth, "Ordinary and Extraordinary Refractive Indices for $Al_xGa_{x-1}N$ Epitaxial Layers," *Appl. Phys. Lett.*, **75**(1), 5 July 1999, pp. 67-69.

2. Scientific Personnel Supported

- John Burk (Undergraduate, graduated 5/98)
- Grady Webb-Wood (Undergraduate, graduated 5/01)
- James Joseph (Undergraduate, graduated 5/01)
- Ümit Özgür (Graduate Student)
- Chang-Won Lee (Graduate Student)
- Arup Neogi (Post Doctoral Researcher)
- Matthew Beaky (Post Doctoral Researcher)
- Kyle Ferrio (Post Doctoral Researcher)

3. Inventions

None

4. Forward

Ultrasmall optical pumped far infrared laser cavities were constructed using defect cavities in a purely dielectric photonic crystal. Microwave measurements were performed on scale model photonic crystals to understand the performance of the cavities as a function of cavity size, isolation, and dielectric loss. In addition, continuous wave and ultrafast optical measurements of wide bandgap semiconductors were performed. Refractive indices were measured for AlGaN comprehensively for the first time. Measurements of conduction band offsets of AlGaN were attempted. The electron capture time in an InGaN multiple quantum well laser structure was found to be approximately 0.5 ps when electrons are optically injected near the barrier band edge. Coherent oscillations of zone folded longitudinal acoustic phonons were observed, and the means for their generation were studied. Finally, these phonons were coherently controlled, and complete cancellation of optically generated acoustic phonons was demonstrated for the first time.

4. Statement of the Problem Studied

The original focus of this proposal was to demonstrate an ultrasmall optically pumped far infrared (OPFIR) laser based on a photonic band gap (PBG) crystal cavity. Photonic crystal cavities would be constructed in the microwave regime before being scaled down to the millimeter wave regime for OPFIR construction. Subsequently, the laboratory began a new research direction to study ultrafast optical properties of wide bandgap semiconductors.

5. Summary of Scientific Progress and Accomplishments

As mentioned above, the original focus of this proposal was to demonstrate an ultrasmall optically pumped far infrared (OPFIR) laser based on a photonic band gap (PBG) crystal cavity. Many of the proof-of-concept building blocks necessary to demonstrate this novel type of laser were demonstrated during the grant period. Pure and doped two dimensional PBG crystals were constructed, and their transmissivity was measured as a function of wavelength, incidence angle,

crystal size, and doping configuration. Work concentrated on the measurement of properties of PBG crystals with point, channel, and lateral defects. Extensive measurements were made of the properties of two-dimensional photonic crystal Fabry-Perot cavity modes, and a millimeter-wave photonic crystal cavity was fabricated and characterized.

However, the primary direction of the research program changed in 1998 when we began constructing a new lab to perform ultrafast optical characterization of wide bandgap III-nitride semiconductors in collaboration with Prof. H. Craig Casey of the Duke Electrical Engineering Department. The first results from that lab involved the measurement of the refractive indices of AlGaN. Later, a mode-locked Ti:Sapphire laser was purchased and ultrafast measurements of carrier capture in InGaN multiple quantum wells were performed. This work concluded with the generation and control of zone-folded acoustic phonons in this multiple quantum well structure.

Two Dimensional Photonic Crystal

The properties of lossless, purely dielectric PBG crystals have been calculated and measured for several years now. However, there had been little theoretical or experimental work dealing with PBGs composed of lossy dielectric material and how that loss affects the transmissivity of perfectly periodic PBG crystals or the cavity Q of PBG crystals with defects. A thorough understanding of how PBG cavities could be constructed and how their properties vary as a function of construction parameters (defect placement within PBG crystal, dielectric loss, surface termination) was necessary before PBG-based OPFIR cavities can be constructed.

Undergraduates John Burk and James Joseph and post doctoral student Matthew Beaky undertook an experimental investigation of two two-dimensional PBG crystals constructed of 0.25" dielectric rods (ε =12) arranged in a triangular and square lattice, respectively, with lattice constant □1cm. As predicted, the resulting band gap occurred between approximately 5-8 GHz for one polarization (TM) for all rotational orientations of the crystal.

The focus of our investigations was to calculate and measure Fabry-Perot (FP) cavity modes formed by splitting 2D photonic crystals in half laterally. The photonic crystal (PC) halves acted as mirrors whose reflectivity could be changed by changing the thickness (number of rows) of the PC. The transmissivity of the 2D PC FP was measured using a swept microwave oscillator source, free space propagation through the 2D PC FP, and detection by either a network analyzer or a crystal detector. As expected, it was observed that the frequency of the cavity modes depended on the separation of the "mirrors" and the $Q = \nu/\Delta\nu$ of the cavity mode increased with increasing mirror thickness. However, attempts to model this behavior as if the PC mirrors were partially reflecting planar mirrors revealed unexpected richness in the resonator performance.

Following this an investigation of two types of microwave cavities was undertaken by undergraduate student, James Joseph. In the first case, channel defects were placed in a line from the front to the back of photonic crystals. The thickness of the PC was varied, and waveguide transmission was studied as a function of channel width and channel length. The ends of these so-called "waveguide" defects were then plugged with dielectric rods in order to form channel cavities, and the cavity wavelengths and Qs were measured (Figure 1). Initial indications revealed that the mode structure was more complex than would be expected for a metal waveguide of similar dimensions. This suggested that the photonic crystal surface produced a more complex, distributed feedback reflection. At the end of the grant, these data were being analyzed as a function of channel width to explore the transition from Fabry-Perot behavior (infinite width, variable length) to waveguide behavior (variable width and length) to single defect.

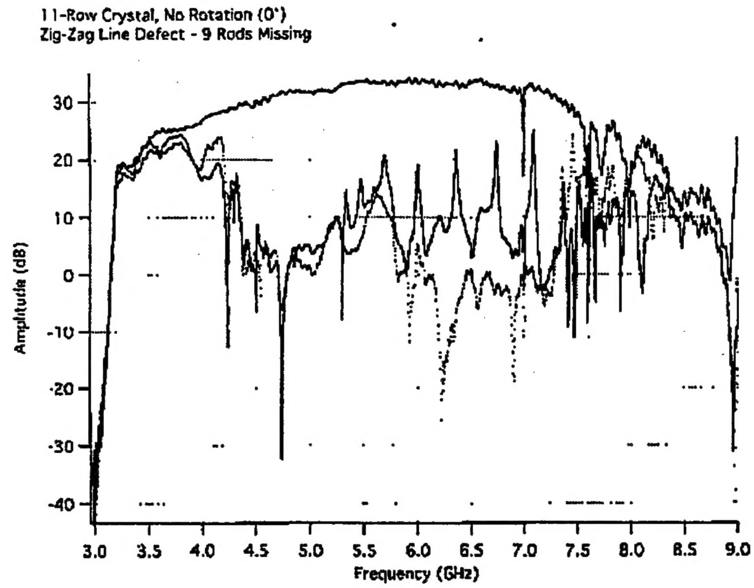

Figure 1: This 11 row, triangular lattice photonic crystal has a 9 row long, 1 row wide channel defect centered in it. The two ends are capped with a single rod, making this defect approximate a waveguide cavity with leaky end mirrors. However, the mode frequencies do not correspond to this geometry due to the zigzag corrugation of the PBG side walls.

The other sort of microwave cavity was formed by starting with a Fabry-Perot cavity. Dielectric rods were progressively added to the outer edges of the cavity, and cavity properties measaured, until only a single rod defect was left in the middle of the crystal. By plotting the frequency and Q of the cavities as a function of the cavity size, he was able to demonstrate expected and unexpected behavior. A comprehensive set of measurements had been made by the end of the grant period, demonstrating that only marginal increases in cavity Q and frequency are gained by adding dielectric rods until the remaining cavity is only a few rods in dimension. After that, the Q and frequency changed perceptibly but not as dramatically as had been expected. We speculate that this behavior also arises from the important role of dielectric loss in the rods.

Finally, a hexagonal 2D PC FP was constructed with a band gap near 250GHz for use as the cavity in an OPFIR. Initial tests using a tunable millimeter wave source at Ohio State Univ. and calculations on the crystal structure suggested that modifications to the structure would be required. Unfortunately, Matthew Beaky, who constructed this cavity finished his tenure as an NRC post doc before this project could be completed.

Ultrafast Characterization Facility

<u>Index of Refraction Measurements</u>

In 1998, we began to build a new facility to characterize wide bandgap III-nitride materials. We first measured the ordinary and extraordinary refractive indices of $Al_xGa_{1-x}N$ samples for $0<x<0.2$ using a prism coupling technique. Laser sources included multiple lines from an Ar^+ laser, a HeNe laser, a cw Ti:Sapphire laser, and diode lasers operating in the near IR. Highly accurate measurements revealed a systematic dependence of the refractive indices as a function of wavelength and mole fraction x. Very little data of this kind is available in the literature for these technologically important materials, and our observations are the first to show quantitatively how the indices vary with λ *and* x. Near the end of the grant period, Prof. Morkoc of VCU grew samples that would allow us to measure the refractive indices of AlGaN containing up to 100% Al. Undergraduate researcher Grady Webb-Wood completed those measurements prior to his graduation in 2001. Our findings provided the first systematic measurement of the ordinary and extraordinary refractive indices of AlGaN throughout the visible wavelength region for all Al mole fractions.

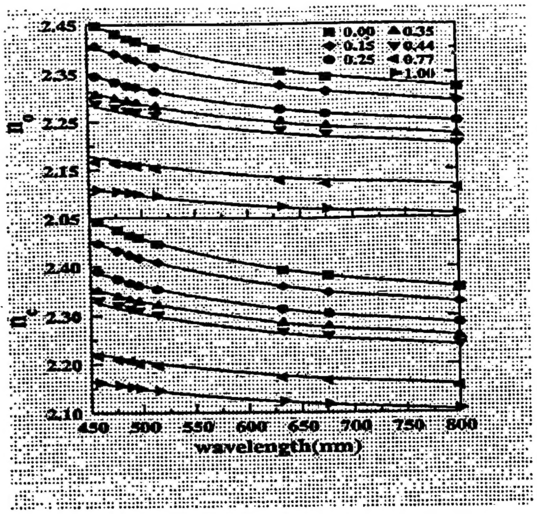

Figure 2. Ordinary and extraordinary refractive indices of AlGaN for Al mole fractions from 0% to 100% throughout the visible wavelength region.

More importantly, these measurements finally reconciled the disparate measurements in the literature. By parameterizing our data and others as a function of band gap energy instead of Al mole fraction, we were able to show that variations in measurements from group to group resulted from differing growth conditions. Our result provides a universal way of predicting the refractive indices simply by measuring the bowing parameter of the samples.

As the grant period ended, we began a collaboration with Prof. John Muth of NC State Univ. to perform similar index measurements on the orthorhombic semiconductor ZnSiN. These materials are presumably uniaxial dielectric with greater complexity than the uniaxial AlGaN materials measured previously. A new apparatus was constructed which would allow the sample to be rotated azimuthally to measure the full rotational variation of refractive index.

Conduction Band Offset Measurements

We also were interested in measuring the conduction band offset of $Al_xGa_{1-x}N$ samples, another poorly known but critical parameter. Samples were received from Northwestern Univ. for this study, but the measurements performed at the Vanderbilt Univ. FEL were inconclusive. We concluded that new samples would be required, designed with doping profiles that would minimize these effects by using this same model. In 2000, Prof. Teitsworth and his student, Alex Makarovski, developed a model that allows us to design these samples with the appropriate doping profile. Prof. Morkoc and NRC post doc Arup Neogi attempted to grow these samples but found the doping was more difficult than expected and that nitrogen-terminated surfaces were much harder to produce than gallium-terminated surfaces. As a result, the measurements on these improved samples were also inconclusive.

Carrier Capture and Coherent Phonon Measurements

We also developed the capability to perform sub-picosecond optical characterization of wide bandgap III-nitride materials. This collaborative project involved researchers in the Duke EE and Physics Departments. Samples were provided from Steve DenBaars of UCSB through a DARPA contract with Craig Casey of Duke EE, and from unpaid collaborators Hadis Morkoc of VCU and John Muth and Saleh Bedair of NCSU. Our long-term goal was to develop the capability to do photoluminescence, photoluminescence excitation spectroscopy, degenerative and non-degenerative differential transmission, and four wave mixing in the challenging blue-UV spectral region. A successful proposal to the Lord Foundation and monies available from the DARPA grant allowed us to purchase a commercial mode-locked Ti:Sapphire laser and a UV He:Cd laser for PL. These systems were operational in 2000.

Finally, we continued measurements on a single MQW InGaN sample from the S. DenBaars group of UCSB. Photoluminescence and photoluminescence excitation spectroscopy was performed on each sample to identify the peak emission and absorption wavelengths. Using

wavelength degenerate differential transmission (DT) measurements, electron capture times were measured to be approximately 0.5ps when electron-hole pairs were created within 50 meV of the barrier energy. Oscillations in the DT data were also observed when the sample was pumped near the barrier energy, oscillations which arose from coherent zone-folded acoustic phonons (ZFLAPs). In 2000, we studied the generation of these coherent ZFLAPs by varying the pump wavelength and intensity and the sample temperature. We observed that the strength of the oscillations increased linearly with pump intensity, but there was no temperature dependence observed. The oscillations are seen as a result of the quantum confined Franz-Keldysh effect through which the acoustic phonons indirectly modulate the location of the barrier absorption edge. The differential transmission technique monitors the resulting change in transmission coefficient, meaning that the oscillations can only be observed at wavelengths very near the barrier band edge.

Near the end of the grant period, we observed that these oscillations could be coherently controlled by a two-pump differential transmission technique. The second pump could be time-delayed with respect to the first pump to induce ZFLAP oscillations that are in-phase or out-of-phase with the ZFLAP oscillations induced by the first pump. Because of the surprising harmonic purity of the oscillations, we were able to demonstrate the first complete cancellation of generated acoustic phonons in any materials system (Figure 3). This result was published by *Physical Review Letters* in the summer of 2001.

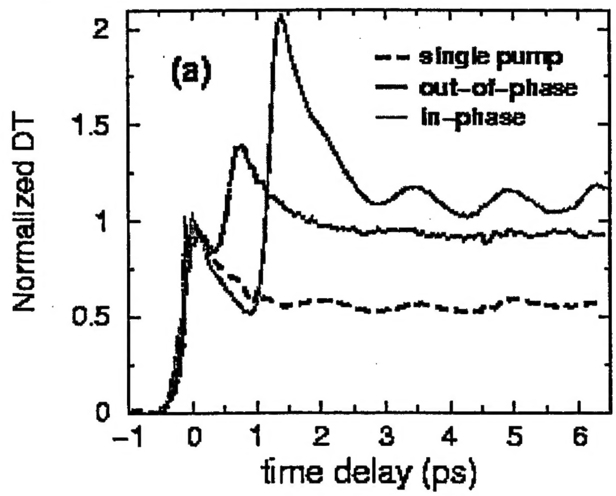

Figure 3. Generation and control of coherent ZFLAP oscillations, demonstrating the enhancement and cancellation of acoustic phonons in an InGaN MQW.